2.1 Introduction

The discoveries of X-rays and radioactivity at the end of the nineteenth century represented major events for medicine that have paved the way for extraordinary diagnostic and therapeutic techniques whose potential has still not been fully exploited. Nowadays, radiation is used in medicine for diagnosis and treatment of many diseases. It has been estimated that each year, worldwide, about 2 billion radiological and diagnostic procedures are performed while about 5.5 million patients are treated with radiation therapy for cancer.

Shortly after the introduction of different types of radiation as techniques for diagnosis and therapy, it became clear that there were not only beneficial effects derived from the possibility of imaging the body and its functions, but also detrimental biological effects from excessive exposure to these extremely powerful forms of energy. These hazards and potential damaging effects became evident long before the physical laws and the biochemical mechanisms underlying radiation-induced biological damage could be understood. With the increased use of radiation in diagnostic and therapeutic applications, concern for the biological effects continues to grow. The need to avoid unwanted radiation exposures has led to the development of the sciences of radiobiology and health physics. By combining knowledge in the fields of physics, biology, chemistry, statistics and instrumentation, sets of rules and guidelines for the protection of individuals and populations from the effects of radiation in all its forms have been developed.

Radiation is essentially a form of very fast-moving energy. Types of radiation include electromagnetic radiation, such as visible light, radio, and television waves, ultraviolet (UV) radiation, microwaves and X- and gamma rays. These types of electromagnetic waves may cause ionisation of atoms when they carry enough energy to separate molecules or remove tightly bound electrons from their orbits around atoms. Whereas electromagnetic non-ionising radiation (radio waves, microwaves, radar and low-energy light) disperse energy through heat and increased molecular movement, electromagnetic ionising radiation (X- and gamma rays) can separate molecules or remove electrons from atoms. Other forms of ionising radiation include subatomic particles, such as alpha particles, protons and beta particles, that is, electrically charged particles, and neutrons.

Ionisation is only the initial step in the breaking of chemical bonds, the production of free radicals, biochemical change and molecular damage such as mutations, chromosome aberrations, protein denaturation and eventually disruption of biological processes including missing or abnormal reproductive capacity and cell killing.

Radiation can be distinguished on the basis of different characteristics including origin, physical properties and energy. The effects of radiation will also depend on the physical mass of the target and on the number and frequency of hits on the target. Also, the intrinsic properties of the target determine the outcome of the irradiation. When an entire organism is hit, the effects vary depending on the maturation stage of the components of the organism.

Finally, while the biochemical effects due to irradiation initiate at the time of the interaction of radiation with the biological target, the full appearance of the consequent effects may be delayed for as much as several years.
Normal exposure to radiation can occur as a result of environmental exposure, due to natural and man-made background radiation, and after medical exposure. It can occur as a result of diagnostic procedures, by X-ray or nuclear medicine examination, entailing the use of radiopharmaceuticals emitting mainly gamma rays, and either as a result of radiation therapy with X-rays and electron beams produced by accelerators or after the administration of radioactive elements emitting mainly beta radiation.

### 2.2 Types of Radiation and Interactions Between Radiation and Matter

Ionising radiation consists of particles and electromagnetic radiation. The particles are electrons, protons, neutrons and alpha particles (composed of 2 protons and 2 neutrons). Electromagnetic radiation includes X- and gamma rays. The interaction of radiation with biological matter entails the dispersion of radiation energy by deposition in the matter. The pattern of distribution of energy in tissues and cells affects the extent of biological damage following the irradiation. The quantity of energy which is deposited into the tissue depends on the linear energy transfer (LET), that is, the amount of energy deposited per unit of path (normally expressed in keV/µm of water). Large amounts of energy can be deposited along a short track, in a few cells, by high-LET radiation, such as the alpha particles (whose LET is on the order of 100 keV/µm), which hardly penetrate tissues. Conversely, a small amount of energy is deposited along the path by low-LET (approximately 3.5 keV/µm), highly penetrating electromagnetic radiation, including X- and gamma rays. In the case of low-LET radiation the energy deposition occurs in points that are distant from each other and only a few ionisations result from a single X- or gamma ray. In biological terms it is concluded that high-LET radiation causes more molecular damage per unit of dose than low-LET radiation. This appears to be related to the higher concentration of energy depositions from a single particle in a single cell and also to so-called bystander effects, namely, the response of cells which are not directly hit by radiation but in which there is a gene induction by adjacent irradiated cells and the production of genetic changes which are potentially carcinogenic.

A very conservative approach assumes no dose threshold for the occurrence of biological effects of radiation and assumes that even exposure to background radiation can have a biological effect. Current radiation risk estimates and radiation protection standards and practices are based on the “linear no-threshold (LNT) hypothesis” based mainly on epidemiological data of human subjects exposed to high doses and dose rates, which maintains that any exposure to radiation, even at very low doses, may be harmful and extrapolates low-dose effects from known high-dose effects. This hypothesis states that risk is linearly proportional to dose, without a threshold. It is therefore assumed that every dose, no matter how low, carries with it some risk, that risk per unit dose is constant, additive and can only increase with dose and that biological responses, when apparent, are independent of the dose.

There is no complete agreement about the validity of the “LNT hypothesis” Alternative models in which thresholds do exist have been developed. This view maintains that some doses of radiation do not produce harmful health effects. One definition of low dose is a dose below which it is not possible to detect adverse health effects. This level has been hypothesised to be at 100 mSv (10,000 mrem). Others suggest that such a level is much too high and a more conservative definition of low dose is the level of radiation from the natural background, around or below 4 mSv. Low-dose studies are currently being conducted to investigate the response of cells and molecules. Current knowledge seems to suggest that health risks are either too small to be observed or are nonexistent for doses below 50–100 mSv and that radiation doses that are of a magnitude similar to those received from natural sources encompass a range of hypothetical outcomes, including a lack of adverse health effects. Finally, after exposures to low levels of ionising radiation it is not possible to detect a change in cancer incidence. This is related to the many factors which can produce cancer, the high incidence of cancers in the general population, and the high variable background levels of radiation exposure in the population.

The first physical event for the induction of biochemical alterations following radiation ex-